

Evidence for Direct CP Violation in the Measurement of the Cabbibo-Kobayashi-Maskawa Angle γ with $B^{\mp} \rightarrow D^{(*)}K^{(*)\mp}$ Decays

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We report the measurement of the Cabibbo-Kobayashi-Maskawa CP -violating angle γ through a Dalitz plot analysis of neutral D -meson decays to $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ produced in the processes $B^{\mp} \rightarrow DK^{\mp}$, $B^{\mp} \rightarrow D^* K^{\mp}$ with $D^* \rightarrow D\pi^0$, $D\gamma$, and $B^{\mp} \rightarrow DK^{*\mp}$ with $K^{*\mp} \rightarrow K_S^0 \pi^{\mp}$, using 468 million $B\bar{B}$ pairs collected by the BABAR detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. We measure $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180°), where the first error is statistical, the second is the experimental systematic uncertainty, and the third reflects the uncertainty in the description of the neutral D decay amplitudes. This result is inconsistent with $\gamma = 0$ (no direct CP violation) with a significance of 3.5 standard deviations.

The breaking of the CP symmetry in the quark sector of the electroweak interactions arises in the standard model from a single irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. This phase can be measured using a variety of methods involving B -meson decays mediated by either only tree-level or both tree- and loop-level amplitudes. The comparison of these two classes of measurements tests the CKM mechanism, thus offering a strategy to search for new physics [2]. The angle γ of the unitarity triangle, defined as $\arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$, where V_{ij} are elements of the CKM matrix, is particularly relevant since it is the only CP -violating parameter that can be cleanly determined using solely tree-level B -meson decays. Its precise determination constitutes an important goal of present and future experiments in flavor physics.

In $B^\mp \rightarrow DK^\mp$ decays [3,4] the color-favored $B^- \rightarrow D^0 K^-$ ($b \rightarrow c\bar{u}s$) and the color-suppressed $B^- \rightarrow \bar{D}^0 K^-$ ($b \rightarrow u\bar{c}s$) transitions [5] interfere when the D^0 and \bar{D}^0 decay to a common final state [6]. The two interfering amplitudes differ by a factor $r_B e^{i(\delta_B \mp \gamma)}$, where r_B is the magnitude of the ratio of the amplitudes $\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)$ and $\mathcal{A}(B^- \rightarrow D^0 K^-)$, and δ_B is their relative strong phase. An amplitude analysis of the Dalitz plot (DP) of D^0 and \bar{D}^0 mesons decaying into the $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ self-conjugate final states from $B^\mp \rightarrow DK^\mp$ decays offers a unique way to access the complex amplitude ratios and thus the weak and strong phases, and r_B . The experimental sensitivity to γ arises mostly from regions in the DP where Cabibbo-favored and doubly-Cabibbo-suppressed amplitudes interfere, and from regions populated by CP eigenstates; thus the uncertainty in γ depends on $1/r_B$ ($r_B \sim 0.1-0.2$).

In this Letter we study the interference between color-favored and color-suppressed transitions as a function of the position in the DP of squared invariant masses $s_- = m^2(K_S^0 h^-)$, $s_+ = m^2(K_S^0 h^+)$, where h represents π or K , for three related B decays, $B^\mp \rightarrow DK^\mp$, $B^\mp \rightarrow D^* K^\mp$, and $B^\mp \rightarrow DK^{*\mp}$ [4,7], and report the most precise single measurement of the complex amplitude ratios and evidence for direct CP violation. We use the complete data sample of 425 fb^{-1} of integrated luminosity at the $Y(4S)$, corresponding to $468 \times 10^6 B\bar{B}$ pairs, and 45 fb^{-1} at a center-of-mass (c.m.) energy 40 MeV below the $Y(4S)$, recorded by the BABAR experiment [8] at the PEP-II asymmetric-energy e^+e^- collider at SLAC from 1999 to 2008. This measurement updates our previous results based on a partial sample of $383 \times 10^6 B\bar{B}$ pairs, from which we reported a significance of direct CP violation ($\gamma \neq 0$) of 3.0 standard deviations, while most of the analysis details remain unchanged [9]. The Belle Collaboration using $B^\mp \rightarrow D^{(*)} K^\mp$, $D \rightarrow K_S^0 \pi^+ \pi^-$ alone [10] has also reported $\gamma \neq 0$ with a significance of 3.5 standard deviations.

We reconstruct a total of eight signal samples, $B^\mp \rightarrow D^{(*)} K^\mp$ and $B^\mp \rightarrow DK^{*\mp}$, with $D^* \rightarrow D\pi^0$, $D\gamma$, $K^{*\mp} \rightarrow K_S^0 \pi^\mp$, with selection criteria nearly identical to our pre-

vious analysis. The $DK^{*\mp}$ final state, for $D \rightarrow K_S^0 K^+ K^-$, has been considered for the first time. For $K_S^0 \rightarrow \pi^+ \pi^-$ candidates, we further require the decay length (defined by the K_S^0 production and decay vertices) projected along the K_S^0 momentum to be greater than 10 times its error. This additional requirement helps to reduce to a negligible level background events from $D \rightarrow \pi^+ \pi^- h^+ h^-$ decays, and from $a_1(1260)^\mp$ misreconstructed as $K^{*\mp}$. After all the selection criteria the background is completely dominated by random combinations of tracks arising from continuum events, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$, or c). Background contributions from $D \rightarrow K_S^0 K_S^0$ decays are found to be negligible. The B^\mp candidates are characterized using the beam-energy substituted B mass m_{ES} , the difference between the reconstructed energy of the B^\mp candidate and the beam energy in the e^+e^- c.m. frame ΔE , and a Fisher discriminant \mathcal{F} that combines four topological variables optimized to separate continuum events [9]. We retain candidates with the loose requirements $m_{ES} > 5.2 \text{ GeV}/c^2$, $-80 < \Delta E < 120 \text{ MeV}$, and $|\mathcal{F}| < 1.4$, which provide signal and sideband regions while removing poorly reconstructed candidates [11]. The reconstruction efficiencies in a signal region with $m_{ES} > 5.272 \text{ GeV}/c^2$ and $|\Delta E| < 30 \text{ MeV}$ are 26%, 12%, 15%, and 14%, for the DK^\mp , $D^*[D\pi^0]K^\mp$, $D^*[D\gamma]K^\mp$, and $DK^{*\mp}$ final states, respectively, for $D \rightarrow K_S^0 \pi^+ \pi^-$ (and slightly lower for $D \rightarrow K_S^0 K^+ K^-$). These values are about 30%, 40%, 30%, and 20% larger than in our previous analysis, with similar background levels, reflecting improvements in tracking and particle identification. The m_{ES} , ΔE , \mathcal{F} , and (s_-, s_+) distributions for events in the signal region can be found in [11].

The $D^0 \rightarrow K_S^0 h^+ h^-$ decay amplitudes $\mathcal{A}(s_-, s_+)$ are determined using the same data sample through DP analyses of D^0 mesons from $D^{*+} \rightarrow D^0 \pi^+$ decays produced in $e^+e^- \rightarrow c\bar{c}$ events [9,12]. The charge of the low momentum π^+ from the D^{*+} decay identifies the flavor of the D meson. The signal purities of the samples are 98.5% and 99.2%, with about 541 000 and 80 000 candidates, for $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$, respectively. The dynamical properties of the P - and D -wave amplitudes are parametrized through intermediate resonances with mass-dependent relativistic Breit-Wigner (BW) or Gounaris-Sakurai propagators, Blatt-Weisskopf centrifugal barrier factors, and Zemach tensors for the angular distributions [13]. The $\pi\pi$ S -wave dynamics is described through a K -matrix formalism with the P -vector approximation and 5 poles [9,14]. For the $K\pi$ S -wave we include a BW for the $K_0^*(1430)^\mp$ state with a coherent nonresonant contribution parametrized by a scattering length and effective range similar to those used to describe $K\pi$ scattering data [15]. For the $K\bar{K}$ S -wave, a coupled-channel BW is used for the $a_0(980)$ with single BWs for $f_0(1370)$ and $a_0(1450)$ states. Overall, the amplitude models reproduce well the DP distributions [12]. Monte Carlo (MC) studies show that a significant contribution to the discrepancies arise from imperfections modeling the efficiency variations at the

boundaries of the DP and the invariant mass resolution. We account for these and other imperfections in the modeling of the D^0 decay amplitudes through our model systematic uncertainties.

We perform a simultaneous, unbinned, and extended maximum-likelihood fit (referred to as CP fit) to the $B^{\mp} \rightarrow D^{(*)}K^{\mp}$ and $B^{\mp} \rightarrow DK^{*\mp}$ decay rates $\Gamma_{\pm}^{(*)}$ and $\Gamma_{s\pm}$ as a function of m_{ES} , ΔE , \mathcal{F} , and (s_-, s_+) [9,11]. We extract the signal and background yields, along with the CP -violating parameters $\mathbf{z}_{\pm}^{(*)} \equiv x_{\pm}^{(*)} + iy_{\pm}^{(*)}$ and $\mathbf{z}_{s\pm} \equiv x_{s\pm} + iy_{s\pm}$, defined as the B^{\mp} complex amplitude ratios $\mathbf{z}_{\pm}^{(*)} = r_{B^{\mp}}^{(*)} e^{i[\delta_B^{(*)} \mp \gamma]}$ and $\mathbf{z}_{s\pm} = \kappa r_{s\pm} e^{i(\delta_{s\pm} \mp \gamma)}$, respectively. Here, $r_{B^{\mp}}^{(*)}$ and $r_{s\pm}$ are the corresponding magnitude ratios between the $b \rightarrow u$ and $b \rightarrow c$ amplitudes for B^{\mp} decays, $\delta_B^{(*)}$ and δ_s the relative strong phases, and κ an effective hadronic parameter that accounts for the interference between $B^{\mp} \rightarrow DK^{*\mp}$ and other $B^{\mp} \rightarrow DK_S^0 \pi^{\mp}$ decays, as a consequence of the $K^{*\mp}$ natural width [9,16,17]. Assuming no CP violation and neglecting $D^0 - \bar{D}^0$ mixing in $D^0 \rightarrow K_S^0 h^+ h^-$ decays [12,18,19], the relation $\overline{\mathcal{A}}(s_-, s_+) = \mathcal{A}(s_+, s_-)$ holds, where $\overline{\mathcal{A}}$ is the \bar{D}^0 decay amplitude. The $B^{\mp} \rightarrow D^{(*)}K^{\mp}$ [and similarly for $B^{\mp} \rightarrow DK^{*\mp}$ replacing $\mathbf{z}_{\pm}^{(*)}$ and $r_{B^{\mp}}^{(*)}$ by $\mathbf{z}_{s\pm}$ and $r_{s\pm}$, respectively] signal decay rates are then

$$\Gamma_{\pm}^{(*)}(s_-, s_+) \propto |\mathcal{A}_{\mp}|^2 + r_{B^{\mp}}^{(*)2} |\mathcal{A}_{\pm}|^2 + 2\lambda \mathbf{z}_{\mp}^{(*)} \mathcal{A}_{\mp} \mathcal{A}_{\pm}^*,$$

with $\mathcal{A}_{\pm} \equiv \mathcal{A}(s_{\mp}, s_{\pm})$, and $\lambda = +1$ except for $B^{\mp} \rightarrow D^*[D\gamma]K^{\mp}$ where $\lambda = -1$ [20]. We apply corrections for efficiency variations and neglect the invariant mass resolution across the DP [9]. For each signal sample, the following background components are considered: continuum events, $B^{\mp} \rightarrow D^{(*)}\pi^{\mp}$ decays where the pion is misidentified as a kaon [only for $B^{\mp} \rightarrow D^{(*)}K^{\mp}$ samples], and $\Upsilon(4S) \rightarrow B\bar{B}$ [other than $B^{\mp} \rightarrow D^{(*)}\pi^{\mp}$] decays. The reference CP fit requires events to satisfy $|\Delta E| < 30$ MeV, but alternative fits are performed varying the requirements on the m_{ES} , ΔE , and \mathcal{F} variables (e.g. $m_{ES} > 5.272$ GeV/ c^2 or $\mathcal{F} > -0.1$) to study the stability of the results. The probability density functions (PDFs) introduced to describe the signal, continuum, and K/π misidentification components, along with the K/π misidentification yields, are determined using events from signal and $B^{\mp} \rightarrow D^{(*)}\pi^{\mp}$, $Da_1(1260)^{\mp}$ control samples. The PDFs for $B\bar{B}$ background events are obtained from large MC samples with full detector simulations [9].

The CP fit yields 896 ± 35 (154 ± 14), 255 ± 21 (56 ± 11), 193 ± 19 (30 ± 7), and 163 ± 18 (28 ± 6) signal DK^{\mp} , $D^*[D\pi^0]K^{\mp}$, $D^*[D\gamma]K^{\mp}$, and $DK^{*\mp}$ events, respectively, for the $K_S^0 \pi^+ \pi^-$ ($K_S^0 K^+ K^-$) final state. The results for the CP -violating parameters $\mathbf{z}_{\pm}^{(*)}$ and $\mathbf{z}_{s\pm}$ are summarized in Table I. Figure 1 shows the 39.3% and 86.5% two-dimensional confidence-level (C.L.) contours in the \mathbf{z}_{\mp} , \mathbf{z}_{\mp}^* , and $\mathbf{z}_{s\mp}$ planes, corresponding to one- and two-standard deviation regions, including statistical errors

only. The distance between the \mathbf{z}_- and \mathbf{z}_+ central values (and similarly for \mathbf{z}_{s+}^* and \mathbf{z}_{s-}) is equal to $2r_{B^{\mp}} |\sin\gamma|$, and the angle defined by the lines connecting the central values with the origin is 2γ , and thus is a measurement of direct CP violation. Fitting separately the data for $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ final states we find consistent results for all the CP -violating parameters [11].

Experimental systematic errors [9,11] originate from uncertainties in the description of the efficiency variations across the DP, the modeling of the DP distributions for background events containing misreconstructed D mesons, the fractions of continuum, and $B\bar{B}$ background events containing a real D meson with either a negatively or positively charged kaon (or K^*), and from residual direct CP violation in the $B^{\mp} \rightarrow D^{(*)}\pi^{\mp}$ and $B\bar{B}$ background components. We also account for statistical and systematic uncertainties in the m_{ES} , ΔE , and \mathcal{F} PDF shapes for signal and background components, and the K/π misidentification yields. These uncertainties account for effects that arise from the dependence of the m_{ES} and \mathcal{F} PDF shapes on the chosen ΔE signal region, the differences in $B\bar{B}$ background for real and misreconstructed D mesons, and our limited knowledge of the m_{ES} endpoint, the peaking contributions to the small $B\bar{B}$ background, and the e^+e^- c.m. frame. Smaller systematic uncertainties originate from the DP resolution, wrongly reconstructed signal events with a real D and a kaon (or K^*) from the other B meson decay, the selection of B candidates sharing tracks with other candidates, and numerical precision in the evaluation of the PDF integrals. We also account for residual cross feed of $B^{\mp} \rightarrow D^*[D\pi^0]K^{\mp}$ events into the $B^{\mp} \rightarrow D^*[D\gamma]K^{\mp}$ sample (about 5%), and the estimated uncertainty on the hadronic parameter $\kappa = 0.9 \pm 0.1$ in the $B^{\mp} \rightarrow DK^{*\mp}$ sample [9,21].

Assumptions in the D^0 decay amplitude models are also a source of systematic uncertainty [9,11,12]. We use alternative $\mathcal{A}(s_-, s_+)$ models where the BW parameters are varied according to their uncertainties or within the ranges allowed by measurements from other experiments, the reference K -matrix solution [9] is replaced by other solutions [14], and the standard parametrizations are substituted by other related choices. These include replacing the

TABLE I. CP -violating complex parameters $\mathbf{z}_{\pm}^{(*)} = x_{\pm}^{(*)} + iy_{\pm}^{(*)}$ and $\mathbf{z}_{s\pm} = x_{s\pm} + iy_{s\pm}$ as obtained from the CP fit. The first error is statistical, the second is the experimental systematic uncertainty, and the third is the systematic uncertainty associated with the D^0 decay amplitude models.

	Real Part (%)	Imaginary Part (%)
\mathbf{z}_-	$6.0 \pm 3.9 \pm 0.7 \pm 0.6$	$6.2 \pm 4.5 \pm 0.4 \pm 0.6$
\mathbf{z}_+	$-10.3 \pm 3.7 \pm 0.6 \pm 0.7$	$-2.1 \pm 4.8 \pm 0.4 \pm 0.9$
\mathbf{z}_-^*	$-10.4 \pm 5.1 \pm 1.9 \pm 0.2$	$-5.2 \pm 6.3 \pm 0.9 \pm 0.7$
\mathbf{z}_+^*	$14.7 \pm 5.3 \pm 1.7 \pm 0.3$	$-3.2 \pm 7.7 \pm 0.8 \pm 0.6$
\mathbf{z}_{s-}	$7.5 \pm 9.6 \pm 2.9 \pm 0.7$	$12.7 \pm 9.5 \pm 2.7 \pm 0.6$
\mathbf{z}_{s+}	$-15.1 \pm 8.3 \pm 2.9 \pm 0.6$	$4.5 \pm 10.6 \pm 3.6 \pm 0.8$

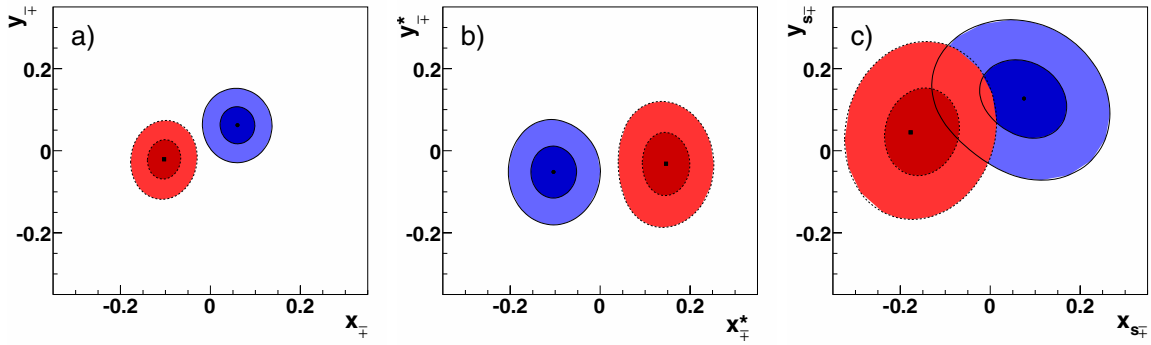


FIG. 1 (color online). Contours at 39.3% (dark) and 86.5% (light) two-dimensional C.L. in the (a) Z_{\mp} , (b) Z_{\mp}^* , and (c) $Z_{s\mp}$ planes, corresponding to one- and two-standard deviation regions (statistical only), for B^- (solid lines) and B^+ (dotted lines) decays.

Gounaris-Sakurai and $K\pi$ S -wave parametrizations by BW line shapes, removing the mass dependence in the P vector [22], changes in form factors such as changes in the Blatt-Weisskopf radius, and adopting a helicity formalism [13] to describe the angular dependence. Other models are built by removing or adding resonances with small or negligible fractions. We find that the overall amplitude model uncertainty on the CP parameters are dominated by alternative models built to account for experimental systematic effects in the determination of $\mathcal{A}(s_-, s_+)$ using tagged D mesons [12]. The statistical errors and variations in the $\mathcal{A}(s_-, s_+)$ model parameters with and without $D^0 - \bar{D}^0$ mixing are also propagated to $Z_{\mp}^{(*)}$ and $Z_{s\mp}$.

Experimental and amplitude model systematic uncertainties [11] have been reduced with respect to our previous

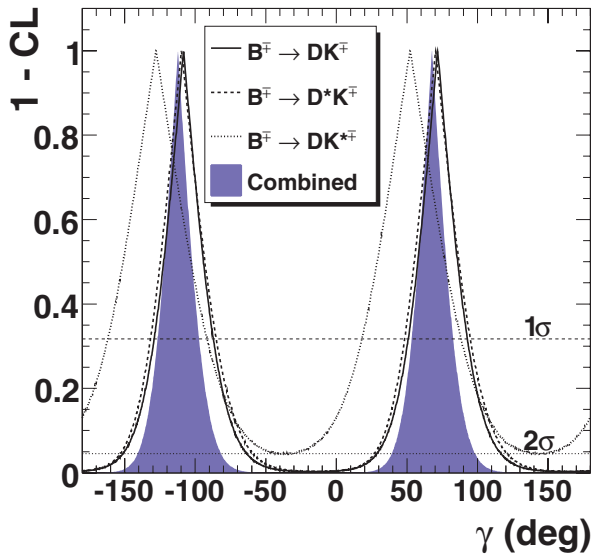


FIG. 2 (color online). $1 - \text{C.L.}$ as a function of γ for $B^- \rightarrow DK^+$, $B^- \rightarrow D^*K^+$, and $B^- \rightarrow DK^{*+}$ decays separately, and their combination, including statistical and systematic uncertainties. The dashed (upper) and dotted (lower) horizontal lines correspond to the one- and two-standard deviation intervals, respectively.

measurement [9] as consequence of the use of larger data and MC samples, and the smaller experimental systematic contributions to the model uncertainty resulting from the improvements in the analysis of tagged D mesons [12].

A frequentist construction of one-dimensional confidence intervals of the physically relevant parameters $\mathbf{p} \equiv (\gamma, r_B, r_B^*, \kappa r_s, \delta_B, \delta_B^*, \delta_s)$ based on the vector of measurements $\mathbf{z} = (Z_-, Z_+, Z_-^*, Z_+^*, Z_{s-}, Z_{s+})$ and their correlations [11] has been adopted [9]. The procedure takes into account unphysical regions which may arise since we allow B^- and B^+ events to have different $r_{B^{\mp}}^{(*)}$, $r_{s\mp}$ in the \mathbf{z} measurements. Figure 2 shows $1 - \text{C.L.}$ as a function of γ for each of the three B decay channels separately and their combination. Similar scans for $r_B^{(*)}$, κr_s , $\delta_B^{(*)}$, and δ_s can be found in [11]. The method has a single ambiguity in the weak and strong phases. The results for all the \mathbf{p} parameters are listed in Table II. The significances of direct CP violation ($\gamma \neq 0$) are $1 - \text{C.L.} = 6.8 \times 10^{-3}$, 5.4×10^{-3} , 6.3×10^{-2} , and 4.6×10^{-4} , which correspond to 2.7, 2.8, 1.9, and 3.5 standard deviations, for $B^- \rightarrow DK^+$, $B^- \rightarrow D^*K^+$, $B^- \rightarrow DK^{*+}$, and their combination, respectively.

TABLE II. The 68.3% and 95.4% one-dimensional C.L. regions, equivalent to one- and two-standard deviation intervals, for γ , $\delta_B^{(*)}$, δ_s , $r_B^{(*)}$, and κr_s , including all sources of uncertainty. The values inside $\{\}$ brackets indicate the symmetric error contributions to the total error coming from experimental and amplitude model systematic uncertainties.

Parameter	68.3% C.L.	95.4% C.L.
γ ($^\circ$)	$68_{-14}^{+15} \{4, 3\}$	$[39, 98]$
r_B (%)	$9.6 \pm 2.9 \{0.5, 0.4\}$	$[3.7, 15.5]$
r^*B (%)	$13.3_{-3.9}^{+4.2} \{1.3, 0.3\}$	$[4.9, 21.5]$
κr_s (%)	$14.9_{-6.2}^{+6.6} \{2.6, 0.6\}$	<28.0
δ_B ($^\circ$)	$119_{-20}^{+19} \{3, 3\}$	$[75, 157]$
δ_B^* ($^\circ$)	$-82 \pm 21 \{5, 3\}$	$[-124, -38]$
δ_s ($^\circ$)	$111 \pm 32 \{11, 3\}$	$[42, 178]$

We have presented a measurement of the $b \rightarrow u$ to $b \rightarrow c$ complex amplitude ratios in the processes $B^{\mp} \rightarrow D^{(*)}K^{\mp}$ and $B^{\mp} \rightarrow DK^{*\mp}$, using a combined DP analysis of $D \rightarrow K_S^0\pi^+\pi^-$ and $D \rightarrow K_S^0K^+K^-$ decays. The results have improved precision and are consistent with our previous measured values [9] and with those reported by the Belle Collaboration with $D \rightarrow K_S^0\pi^+\pi^-$ alone [10], and with determinations based on other D meson final states [21,23,24]. From our measurement we determine $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180°), exclude the no direct CP -violation hypothesis (i.e., $\gamma = 0$) with a C.L. equivalent to 3.5 standard deviations, and derive the most precise single determinations of the magnitude ratios $r_B^{(*)}$ and κr_s .

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